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Screening a precipitation stable isotope database for inconsistencies prior to hydrological applications – examples from the Austrian Network for Isotopes in Precipitation

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Abstract:

The ratio between the heavy and light stable isotopes in precipitation (δ_p) is an effective tool in answering questions in hydrology, climatology, biogeochemistry and other disciplines, but only if spatiotemporally sufficient data is available provided by precipitation monitoring networks. However, when gathered into large databases this can contain errors that can severely impact research outcomes. The present study aims to systematically identify and propose, for the first time, a screening procedure and possible adequate solution(s) to database errors detected in precipitation stable isotope monitoring networks in a reproducible way. The proposed approach is a distance-based outlier detection variant heavily relying on empirical inspection of spatially clustered δ_p time series. The core of the methodology consisted of screening the (i) δ^{18}O vs. δ^2H cross plot and (ii) δ_p station time-series, and comparing them to their neighbors by organizing the δ_p monitoring stations into spatial domains. Potential errors were categorized into (i) point anomalies (isolated erroneous data points) and (ii) interval anomalies (sustained errors over time). The approach is demonstrated on the Austrian Network for Isotopes in Precipitation, a data base that collects data on a monthly basis since 1972 with more than 70 active stations at its peak in 2014. In this sense, it is a crucial backbone for understanding hydrological processes in Central Europe. At 10 stations only point anomalies were found, at six stations only interval anomalies (Achenkirch, Bad Bleiberg, Hütten, Lahn, Salzburg, Schoppernau), and at five (Apetlon, Podersdorf, Saalfelden, Villacher Alps, Weyregg) both kind of anomalies were detected. By addressing these errors case-by-case the reliability of a precipitation isotope database for hydrological and climatological research could be enhanced.

1. Introduction

The ratio between the heavy and light stable isotopes in the water molecule (^{18}O/^{16}O;^{2}H/^{1}H) is an effective tool in answering questions in environmental isotope geochemistry, i.e. hydrology, climatology, biogeochemistry etc. (Coplen et al., 2000). Stable isotope composition of oxygen and hydrogen is conventionally expressed as δ values (δ^2H and δ^{18}O respectively) reported in per mille (‰) (Coplen, 1994). The stable isotopic composition of hydrogen and oxygen in precipitation (δ_p) provides an insight into the origin of water vapor, the conditions attained during condensation, and precipitation (Aggarwal et al., 2016; Dansgaard, 1964). Using these variations, water (precipitation) stable isotopes have become important natural tracers in the study of the water cycle (Bowen and Good, 2015; Fórizs, 2003) and ignited the establishment of a global (IAEA, 2023) and few national station networks, such as the Slovenian Network for Isotopes in Precipitation (SLONIP) (Vreča et al., 2022), or the Chinese Network for Isotopes in Precipitation (Liu et al., 2014) collecting precipitation samples and then determining and archiving their δ^2H and δ^{18}O values. The mission of precipitation isotope monitoring networks is to "provide basic isotope data for the use of environmental isotopes in hydro(geo)logical investigations" (Rozanski et al., 1993) within the scope of water resources inventory, planning and development (IAEA, 2023).

Over the past years, work has begun combining monthly δ_p databases, such as Global Network for Isotopes in Precipitation (GNIP) (IAEA, 2023), SLONIP (Vreča et al., 2022), PAPIN (Mellat et al., 2021) etc. on a European scale (Erdélyi et al., 2023; 2024a,b). During the procedure a variety of database errors were found. While some errors may be removed upon database compilation (IAEA, 1992), many remain since such datasets are not rigorously and systematically screened for errors. Research studies extracting δ_p time series from on-line databases typically do not entertain the possibility of erroneous δ_p records or lack the documentation of database screening. In the few positive examples, the secondary isotopic parameter, so-called deuterium excess or d-excess; calculated as $d = \delta^2H - 8 \times \delta^{18}O$ (Dansgaard, 1964) was applied e.g. Bowen et al., (2018); Nelson et al., (2021).

Errors during sample storage, handling, analysis and/or data manipulation can impact stable isotope composition values in the database, producing similar effects as small-scale natural variations (Coplen and Qi, 2009; Nigro et al., 2024). These data-errors and small-scale effects can result in extreme values that are indistinguishable when inspecting data from only a single station. Our hypothesis is that simultaneous examination of δ_p time series from nearby stations can help to differentiate isotopic signals associated with small-scale natural effects and possible database errors. Such database errors may appear only at a single station but may not be reproducible at neighboring stations, even those a few kilometers apart. This is the fundamental idea behind distance-based outlier detection procedures (Muhr and Affenzeller, 2022).

The aim of the present study is to give a step-by-step overview on detecting and handling typical database errors on the example of the Austrian Network for Isotopes in Precipitation (ANIP), one of the largest European national δ_p databases. No study exists to date (i) gathering the different type of database errors related to precipitation stable isotopes and (ii) providing a uniform approach on their detection and handling. The motivation is to inform ongoing research projects about potential or confirmed database errors and to provide corrected time series of precipitation stable isotope composition.

2. Materials and Methods

2.1. Monthly precipitation stable isotope records from Austria and its surroundings

Monthly δ_p values were acquired from precipitation monitoring stations operating in Austria and its vicinity between 1960 and 2022 (Fig. 1).

Austrian Network of Isotopes in Precipitation

The ANIP started operating in 1972 but some samples date back to the 1960s already making it a fundamental pillar among the European precipitation stable isotopic studies (Benischke et al., 2018; Kralik et al., 2003). The ANIP collects isotope data and relevant meteorological data (temperature, precipitation amount) on a monthly basis. The purpose of the ANIP isotope monitoring network as required by Austrian law and operated under the framework of the water quality ordinance (BGBl., 2006) is to provide water authorities with data to improve characterization of local and regional water resources, and to provide input data for hydrological and hydrogeological investigations and a data-base for climatological research (Rank et al., 2016). The measurements were performed at the ARSENAL laboratories in Vienna (Rank et al., 2016). The data are publicly available via https://www.umweltbundesamt.at/umweltthemen/wasser/isotope. The ANIP database (accessed on 01.06.2023) provided 80 stations with δ^2H and/or δ^{18}O data. Beside a single sample from August 2008 at Sieghartskirchen the fewest data (*n*=5) were available at Dienten and Obervermunt, while most data were available at Vienna recording 670 δ^{18}O and 668 δ^2H measurements between February 1961 and October 2022. Most stations began operation in January of 1973, and seven sites namely Vienna, Graz, Klagenfurt, Villacher Alps, Apetlon, Podersdorf, and Moosbrunn provided data to the GNIP (IAEA, 2023). A striking break in the operation was between January 2003 and December 2006 (Fig. 1b) due to administrative reasons.

Neighboring countries along the Austrian border

It is expected that the δ_p monitoring stations closer to each other should provide more similar observations than the ones further apart regardless of national borders (Hatvani et al., 2021). Thus, besides the precipitation stable isotope records available from within the national borders of Austria, additional records were gathered from the neighboring countries along the border and used in the screening process to validate the regional (dis)agreement of potentially erroneous data spotted in the ANIP database. Data from the neighboring countries consisted of mainly GNIP (*n*=9) (IAEA, 2023) and SLONIP (*n*=4) (Vreča et al., 2022) stations, with an additional Hungarian (Kern et al., 2020), and Italian (Cervi et al., 2017) station (Fig. 1a).

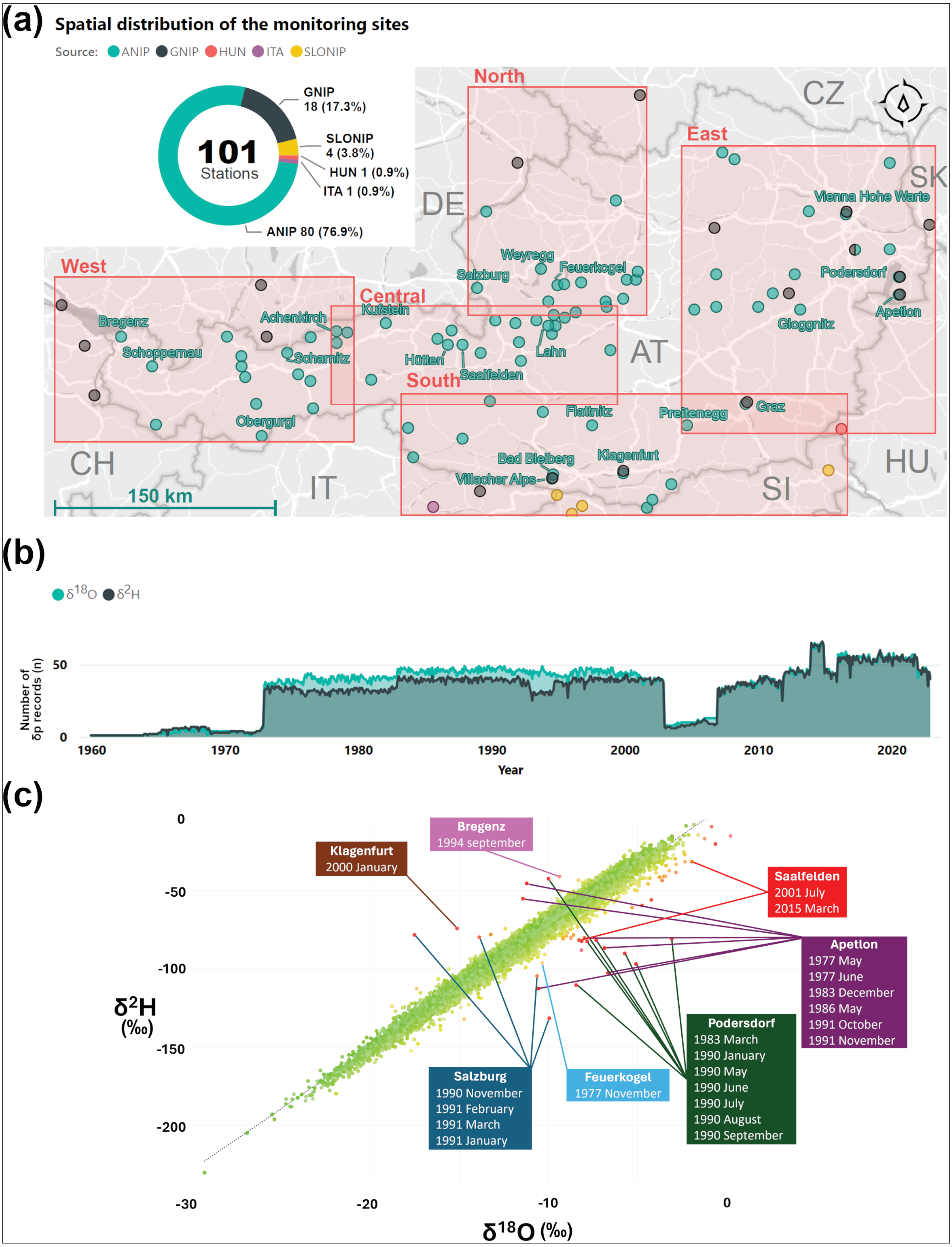

Figure 1: **(a)** Study area, monitoring sites and available data. Map of Austria and the neighboring countries and their δp monitoring sites (dots). The red rectangles indicate the five subregions, the network was divided into. Station groups are marked with the same color in the donut chart and the map. The two-letter country codes follow the ISO 3166-1 alpha-2 standards. **(b)** Number of δp records obtained for the period 1960–2022. **(c)** δ-δ cross plot with the selected anomalies annotated and listed under the station name.

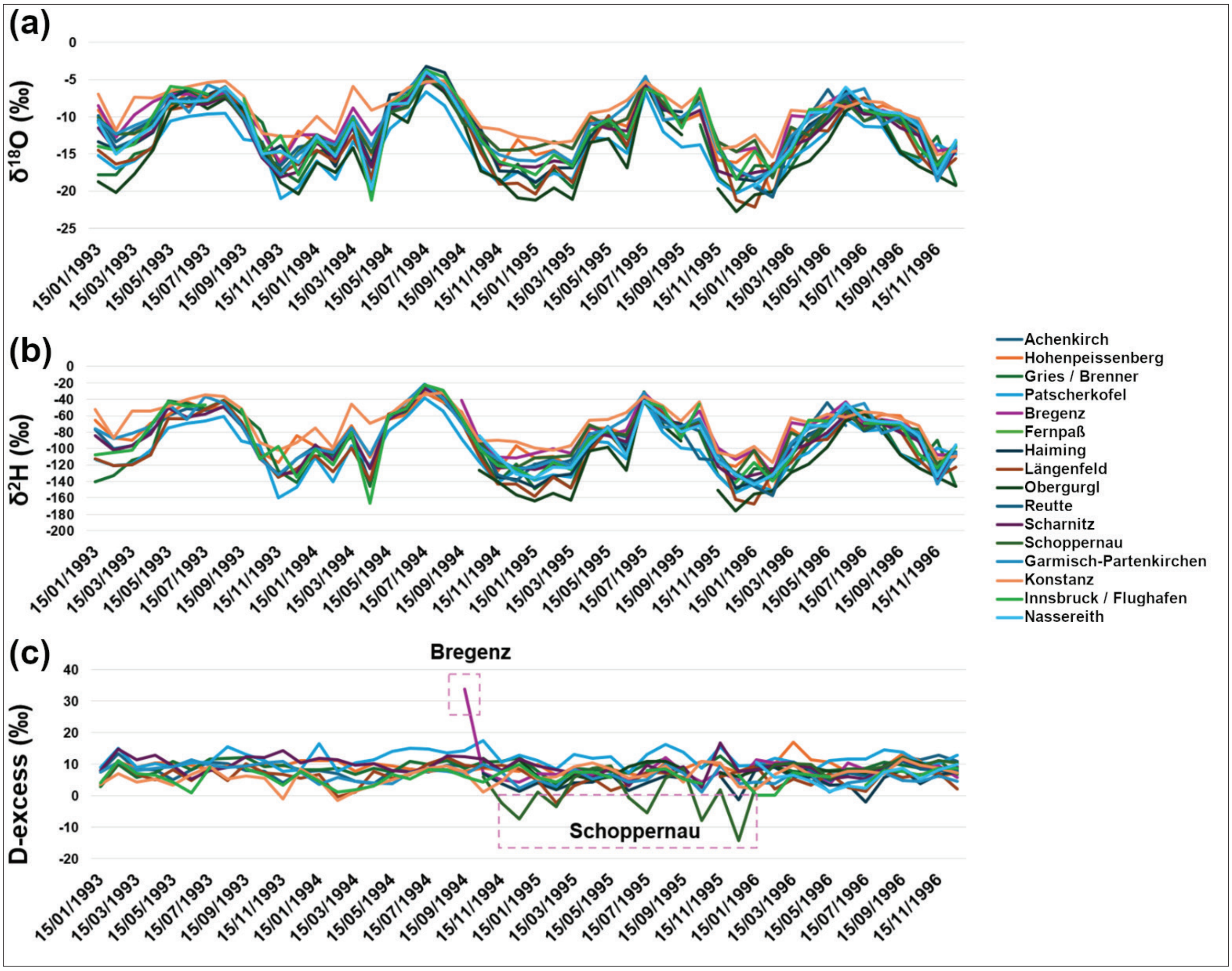

Figure 2: (a) δ18O, **(b)** δ2H and **(c)** *d*-excess time series of precipitation monitoring stations in the West domain between January 1983 and December 1986.

2.2. Methodology

Considering that the physical processes regulating δ_p variations are characterized by considerable spatial autocorrelation (Di Cecco and Gouhier, 2018; Eshel et al., 2022), notable spatial associations among δ_p variations can be securely assumed. Hence, a distance-based outlier screening approach was proposed. The two primary isotopic parameters (δ^{18}O and δ^2H) have a strong linear relationship and is based on a classical concept of hydrology (Gat, 2005) which stems from physical processes (Fórizs, 2005; Putman et al., 2019; Rozanski et al., 1993). Thus, deviations from this linear relationship may result in erroneous δ^{18}O and δ^2H pairs. A relevant screening procedure should consist of the following major steps:

- Investigate the cross plot between δ^{18}O and δ^2H (δ - δ plot) for precipitation to detect outlying values (Fig. 1c). The time series of such seemingly outlying δ_p station data should first be empirically investigated.
- Plotting the problematic stations vs. their neighbors. To facilitate this step, the δ_p monitoring stations' time series should be grouped into domains. These domains should be chosen to enclose climatologically homogeneous areas, which predestine a more coherent isotope hydrometeorological variability among the grouped stations, facilitating the identification of outliers.

In the case of the ANIP five domains were defined (Fig. 1), each contained between 14 to 23 ANIP stations and up to 10 non-ANIP stations. The Central domain included stations overlapping with some in the West (n=3), North (n=4), and South (n=1) domains. Two ANIP stations and two additional ones from the neighboring countries were included both in the East and the South domains. These overlapping areas and the redundant investigation of the stations located within ensure that the spatial associations are seamlessly cross-checked in all directions.

Within these domains, the time series of the two primary (δ^{18}O, δ^2H), and a secondary (d-excess) isotopic parameters of the stations were empirically compared via plots (Figs. 2–5). This step may indicate potential outliers, that were not visible in the cross plot of δ^{18}O vs. δ^2H, since

Site	# of lines with supposed	
	point anomalies	interval anomalies (from – to)
Achenkirch		55 (Oct 1978 – May 1983)
Apetlon	5	3 (Oct 1991 – Dec 1991)
Bad Bleiberg		222 (Dec 1972 – June 1991)
Bregenz	3	
Feuerkogel	1	
Flattnitz	3	
Gloggnitz	1	
Hütten		11 (Oct 2016 – Oct 2017)
Klagenfurt	3	
Kufstein	1	
Lahn		175 (Jan 1973 – Jul 1987)
Obergurgl	2	
Podersdorf	4	5 (May – Sep 1990)
Preitenegg	2	
Saalfelden	2	76 (Jan 1983 – Apr 1989), 135 (Mar 2011 – Dec 2022)
Salzburg		104 (Feb 1983 – Sep 1991)
Scharnitz	3	
Schoppernau		14 (Nov 1994 – Dec 1995)
Vienna Hohe Warte	1	
Villacher Alps	4	10 (Mar 1999 – Dec 1999), 7 (Febr 2001 – August 2001)
Weyregg	1	5 (Mar 2007 – Aug 2007)

Table 1: Inventory of identified point and interval anomalies in the ANIP database (accessed on 01.06.2023).

it entails an in-depth comparison between the neighboring stations, that should be spatially coherent with regionally common signals of δ_p.

In the final screening step, data with questionable quality should be flagged with *expressions of concern/potential explanations, suggested action or correction* (if any) (Tab. S1) analogously to the most common flags used in the GNIP. Subsequently, this guide users working with the database and hopefully help database managers applying official error flags to the database on a case-by-case approach. A consistent framework for flagging data issues supports the standardized quality control of isotope records across different databases and supports a harmonious interoperability based on FAIR data principles (Wilkinson et al., 2016).

The proposed approach follows the principles of distance-based outlier detection (Muhr and Affenzeller, 2022; Shekhar et al., 2003; Smiti, 2020) while relying on empirical inspection of spatially clustered δ_p time series. The insights gained from this process could guide the development of (semi)automated algorithms (e.g., Knorr et al., 2000; Wu et al., 2010) suitable for screening δ_p time series at continental-scales in the future.

3. Results and discussion

During the systematic screening on the example of the ANIP database's records two main types of database-errors were recognized, point anomalies representing a single data point, and interval anomalies representing suspected erroneous data of measurements occasionally up to a decade (Tab. 1). It is considered a point anomaly if the detected inconsistency can be solved by the modification of an isolated value in the record. An interval anomaly is assumed if at least three consecutive values are detected as problematic. The following sections illustrate and document these problematic and suggest a solution to correct them (Tab. S1). Overall, out of the 87 stations 21 had datapoint(s) with confusing values according to the approach applied in the present study.

3.1. Specific errors

Numerous point errors (n=37) were discovered at 15 stations. Most of them (n=5) are located in the Apetlon record in the East domain (Tab. 1). The following paragraph illustrates a specific example.

At Bregenz, the outlier detected in δ-δ plot (Fig. 1c) had an unusually high d-excess value in September 1994

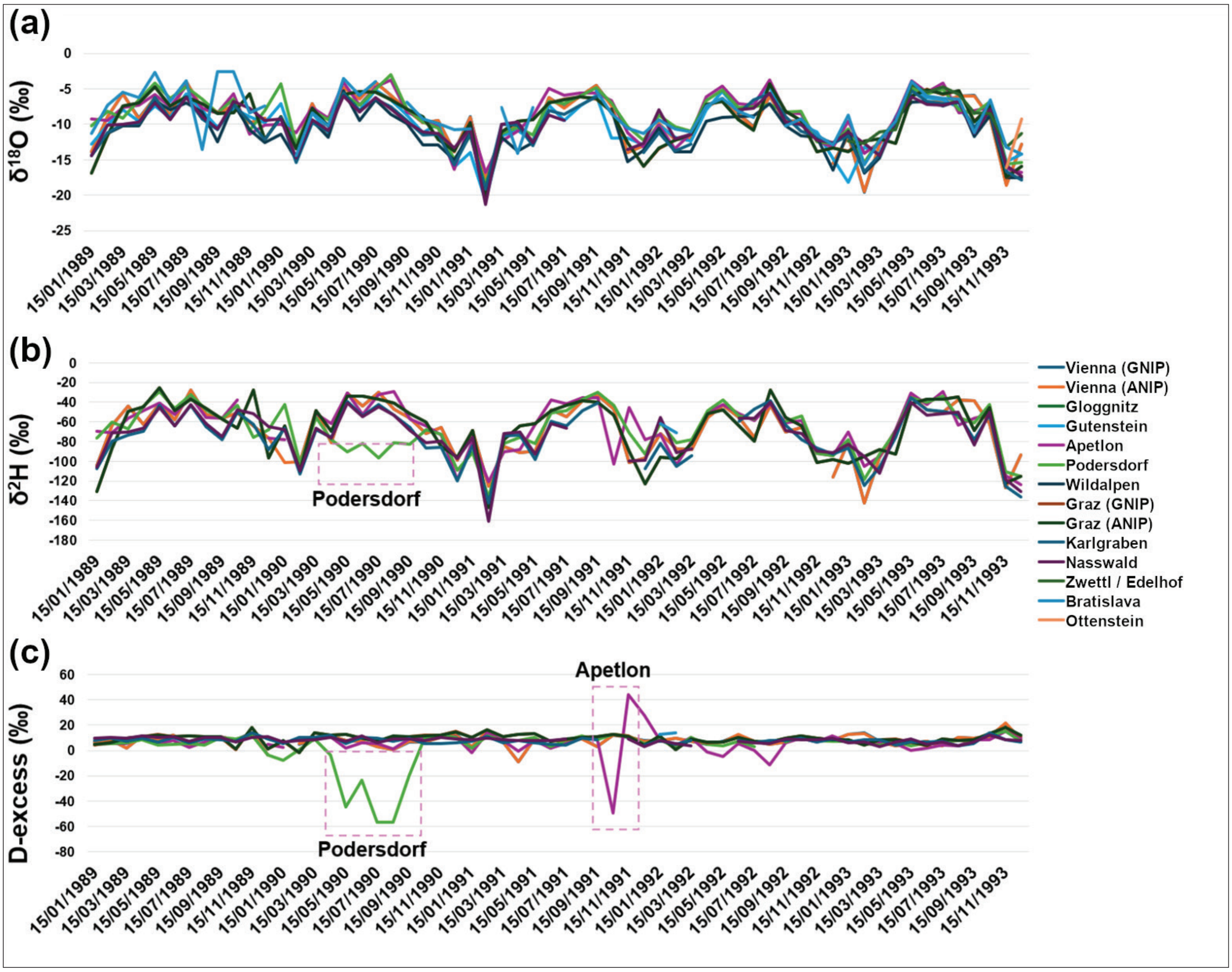

Figure 3: **(a)** $\delta^{18}O$, **(b)** $\delta^{2}H$ and **(c)** *d*-excess time series of precipitation monitoring stations in the East domain. between January 1989 and December 1994.

in the West domain's set of sites (Fig. 2c). Comparing the primary isotopic time series of the stations in the West domain reveals that the $\delta^{18}O$ values match (Fig. 2a), while the $\delta^{2}H$ value of Bregenz is above the range of measured values of the neighboring stations (Fig. 2b). Consequently, it was concluded that this anomalous $\delta^{2}H$ value is causing the extraordinary *d*-excess and it is reasonable for it to be flagged erroneous and neglectable from the database (Tab. S1).

Interval anomalies were identified at eleven stations, with durations ranging from three months to nearly two decades (Tabs. 1 and S1). In the following paragraphs five specific examples are given illustrating some typical situations. At Schoppernau the *d*-excess data showed a tendency to be lower between November 1994 and December 1995 compared to the *d*-excess variability of the surrounding stations in the West domain. More strikingly, the *d*-excess values were even negative on seven occasions (Fig. 2c), despite this never happened before or after, at the Schoppernau station. This observation suggests a sustained evaporation bias. In the former version(s) of the ANIP, isotopic data presumably modified by evaporation effect were usually flagged as *"abgelehnte Werte: … (Verdunstung)"*, meaning *"rejected value: …. (evaporation)"*. Based on the characteristic deviation in d-excess observed between November 1994 and December 1995 both set of $\delta^{18}O$ and $\delta^{2}H$ values of the Schoppernau record could be flagged accordingly.

At Podersdorf, six anomalous monthly values were spotted between January 1990 and September 1990 in the *δ*-*δ* plot (Fig. 1c), which were directly identified by exploring the δ_p values' time series together with the neighboring time series of the East domain (Fig. 3). While the $\delta^{18}O$ data were in agreement with monthly variations recorded at neighboring stations throughout 1990 (Fig. 3a), the $\delta^{2}H$ values lay clearly below the range of the neighboring stations causing weirdly negative d-excess records (Fig. 3c). The $\delta^{2}H$ difference is so substantial (~50‰) for each month in this period that $\delta^{2}H$ data are recommended omit from January 1990 to September 1990 from the Podersdorf station record in hydrological applications.

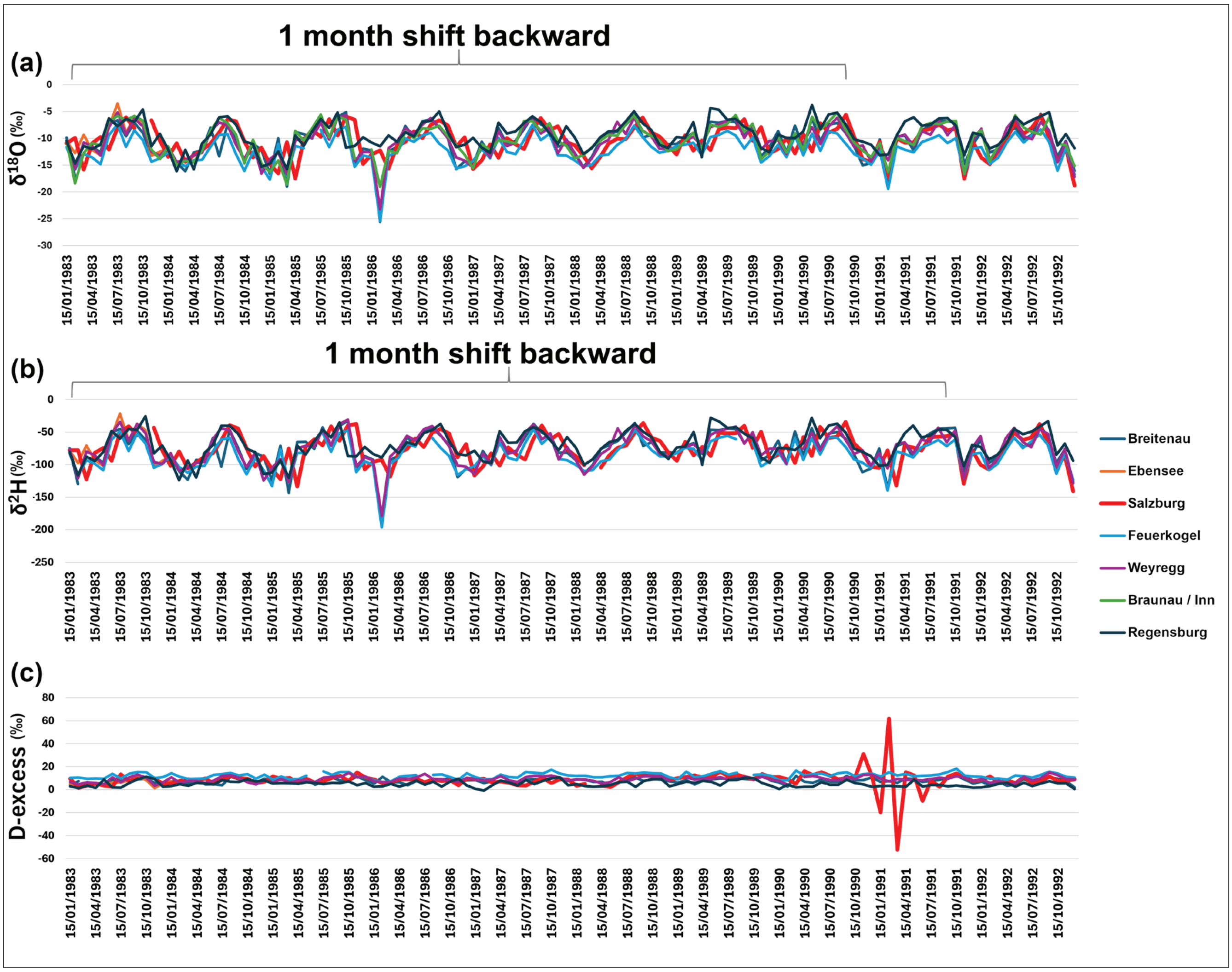

Figure 4: **(a)** $\delta^{18}O$, **(b)** δ^2H and **(c)** *d*-excess time series of the Salzburg precipitation monitoring station and the neighboring stations in the North domain between January 1983 and December 1992. The problematic intervals are annotated in the a and b panels.

At Apetlon, after an extreme negative d-excess value in October 1991, it increased swiftly to an unusually positive value in November and December 1991 (Fig. 3c). Compared with the data from neighboring stations (East region), it was noticeable that the $\delta^{18}O$ record follows the monthly variations well in fall 1991 (Fig. 3a), while δ^2H values from October to December did not fit into the regional pattern (Fig. 3b). We suspected that the discrepant δ^2H values from October to December were wrongly arranged in time. If the δ^2H value in October had changed to December, the δ^2H value in November had changed to October and the δ^2H value in December had changed to November, the *d*-excess values would fit well to the monthly *d*-excess variations documented at the neighboring stations in fall 1991. This suggests that the precipitation δ^2H time series could be corrected by reordering the data as described above (Tab. S1).

At Salzburg, out of the nine months from November 1990 to March 1991 four data points were anomalous in the δ-δ plot (Fig. 1c). By plotting the time series with the neighboring stations even more problematic values appeared indicating a much longer and adverse problem (Tab. 1, Fig. 4). It became evident that both δ^2H and $\delta^{18}O$ data were shifted by one month back in time over an extended period of time (Fig. 4). The beginning of the mismatch for both δ^2H and $\delta^{18}O$ was January 1983. At this date strangely the same δ^2H value was seen in the record as in February 1983 suggesting the erroneous duplication of this value, this might be the reason for the one-month-shift. However, the termination of the mismatch was different for the two primary isotopic parameters. There was again an agreement between the surrounding $\delta^{18}O$ time series and the Salzburg $\delta^{18}O$ record by September 1990 while the δ^2H record only recovered by September 1991 (Fig. 4). Based on these observations the Salzburg record can be corrected by (i) removing both isotopic values from January 1983, (ii) shifting the δ^2H data back in time between February 1983 and September 1991 and (iii) shifting the $\delta^{18}O$ values back in time between February 1983 and September 1990, (iv) leaving a gap in the δ^2H and $\delta^{18}O$ record at September 1990 and September 1991 respectively (Tabs. 1 and S1).

	Hager and Foelsche, 2015		post- suggested corrections (this study)	
Station	**slope**	**intercept**	**slope**	**intercept**
Achenkirch	8	5.6	8.01 ± 0.06	7.31 ± 0.21
Feuerkogel	8.3	15.5	8.26 ± 0.04	15.51 ± 0.25
Klagenfurt	7.9	7.6	7.92 ± 0.04	7.49 ± 0.15
Salzburg	8.1	9	8.11 ± 0.07	9.40 ± 0.20

Table 2: The slope and intercept of the best fit line estimated for the period of 1973–2002 by ordinary least squares Hager and Foelsche (2015) compared to the same parameters calculated from the corrected monthly δ^2H and $\delta^{18}O$ ANIP data.

At Lahn the most complicated case of interval anomaly was encountered. After August 1987 the Lahn δ_p record was in-phase with its neighboring counterparts, while prior to that it was clearly out-of-phase (Fig. 5a), not following the typical regional seasonal pattern (Hager and Foelsche, 2015) which was unexplainable and unprecedented (Figs. 2–4). Exploring the problematic interval further revealed that this mismatch is not constantly present. A four-month forward shift in time was found necessary between January 1973 and July 1976, and a six-month forward shift until July 1985 (Fig. 5b, Tab. S1).

The most peculiar anomaly was observed between January 1986 and July 1987, when reversing the chronological order of the set of values seemed necessary (Fig. 5b, Tab. S1). Besides the visual inspection of the data (Fig. 5c), an additional statistical verification was done. The correlation coefficient was calculated between the (i) in-phase section, the (ii) unmodified out-of-phase section and the (iii) corrected out-of-phase section with its neighbors indicating an improvement after the corrections (r>0.6) (Fig. 5d).

3.2. Effect of errors and their correction on the meteoric water line

The ordinary least squares regression was calculated for four stations after the suggested corrections were made and the parameters of the linear fit (slope and intercept) were compared to the corresponding ones by Hager and Foelsche (2015) for the overlapping time period (1973–2002). At Feuerkogel and Klagenfurt only a single δ^{18}O-δ^2H pair was suggested to be discarded (Fig. 1c), the effect is almost negligible (Tab. 2), while discarding data (e.g. at Achenkirch) (Tab. S1) or shifting data (e.g. at Salzburg) (Fig. 4) for periods of multiple months necessarily caused a remarkable change. For instance, the intercept estimated from the corrected data is larger for both Achenkirch and Salzburg, while that of the original data is outside the estimated uncertainty range suggesting a significant change (Tab. 2). The difference in the estimated regression parameters (slope and intercept) could make a considerable difference impacting isotope hydrological application, for instance the computation of line-conditioned excess (Landwehr and Coplen, 2006).

3.3. (Dis)agreement between ANIP and GNIP times series from mutual stations

If possible, it is suggested to compare the regional with the national databases when screened to the GNIP data, especially if there are stations included in both the explored database and the GNIP. There are seven stations that are included in both ANIP and GNIP networks, out of which Apetlon, Moosbrunn and Podersdorf have no overlap in their operation in the two networks. Thus, it was investigated, how the primary and secondary isotopic values differ within the two networks at stations Graz, Klagenfurt, Vienna and Villacher Alps in the overlapping period.

At the station Graz, there was no difference in the δ^2H data between the GNIP and ANIP data series during the overlapping time period from January 1973 to December 2002. The δ^{18}O values differed by ±0.05‰ attributed to a mere rounding difference) (in the GNIP two decimal places are used, while in the ANIP only one up to January 2001.

On the contrary, there are striking differences between observed GNIP and ANIP values at the three other sites (Fig. 6). There are (i) occasional extreme differences exceeding even a couple of per mille, or (ii) periods with systematic bias. In the next paragraphs some examples are given for the three stations. Explanation(s) provided for only the most obvious cases stemming from comparisons between neighboring records. Note that the order in which the GNIP is compared to the ANIP or vice versa is not intentional, and only those ANIP anomalies are included in Table S1 which were found during the distance-based outlier detection in the first place.

In the case of Vienna, the sampling started in 1961 for the GNIP. After 1973 an additional sampler was installed providing data to the ANIP from the same site (Kralik et al., 2015). Thus, a perfect agreement between the GNIP and ANIP is not expected due to a separate sample collection since then. Despite of this, the differences between the two datasets are minuscule (Fig. 6a), typically in the range of rounding errors (Kralik et al., 2015). Nevertheless, a couple of outliers do exist worth mentioning:

- January 1987: the largest difference in the history of the station, where the δ^{18}O of the ANIP is much higher than the GNIP data.
- February 2002 to August 2002: the δ^2H composition

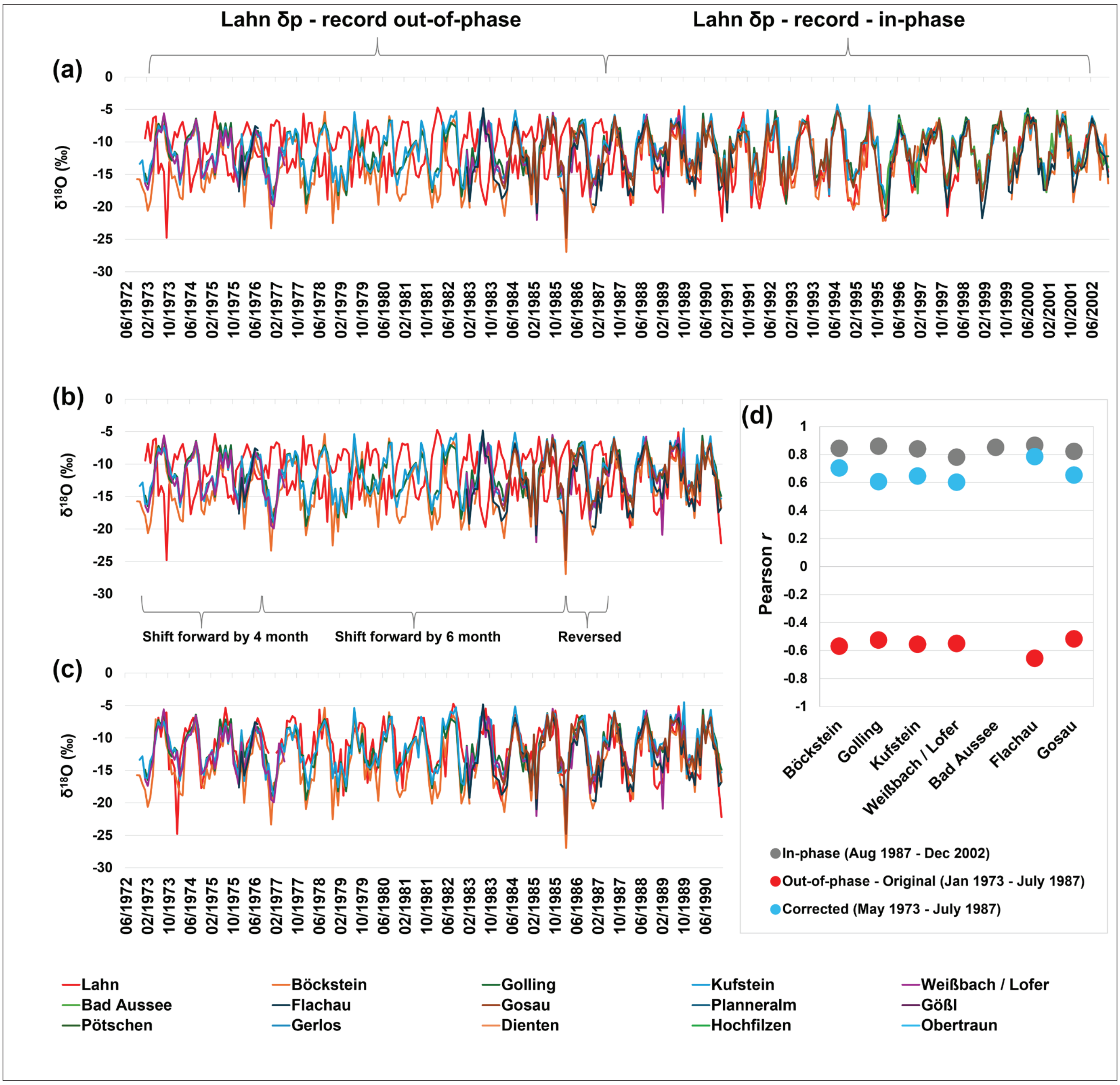

Figure 5: **(a)** δ[18]O time- series of the 1972–2002 Central domain (Fig. 1) record (Lahn highlighted in red), **(b)** the records for 1972–1990 with annotated problems, **(c)** the Central domain records with the corrected Lahn time series and **(d)** the Pearson correlation (Wilcox, 2003) coefficients calculated from between Lahn and the other records. Achenkirch and Saalfelden stations were excluded from the graph since their records are potentially disturbed by a sustained evaporation bias in this period. The horizontal annotations in the (a) and (b) panels refer to the Lahn record.

is more negative in the GNIP compared to the ANIP dataset, the average difference is 2.8‰.

- November 2009: the δ^2H composition is more negative (~12‰) in the GNIP compared to the ANIP dataset.
- May 2019 to end of the study period: the δ^{18}O of the ANIP dataset is systemically more negative than the GNIP by 0.34‰ on average, with an extreme value recorded in May 2020 when the difference was 3.9‰ and 26.7‰ for δ^{18}O and δ^2H, respectively.

In the case of Villacher Alps, the overlapping period covers January 1973 to December 2002, with both primary isotopic parameters available in the two databases (Fig. 6b). The most expressive differences are

- April 1974: the ANIP values are more negative than the GNIP values for both parameters,
- February to March 1975: comparing the time series with the neighboring stations reveals that the GNIP values are swapped between the two months for both parameters,

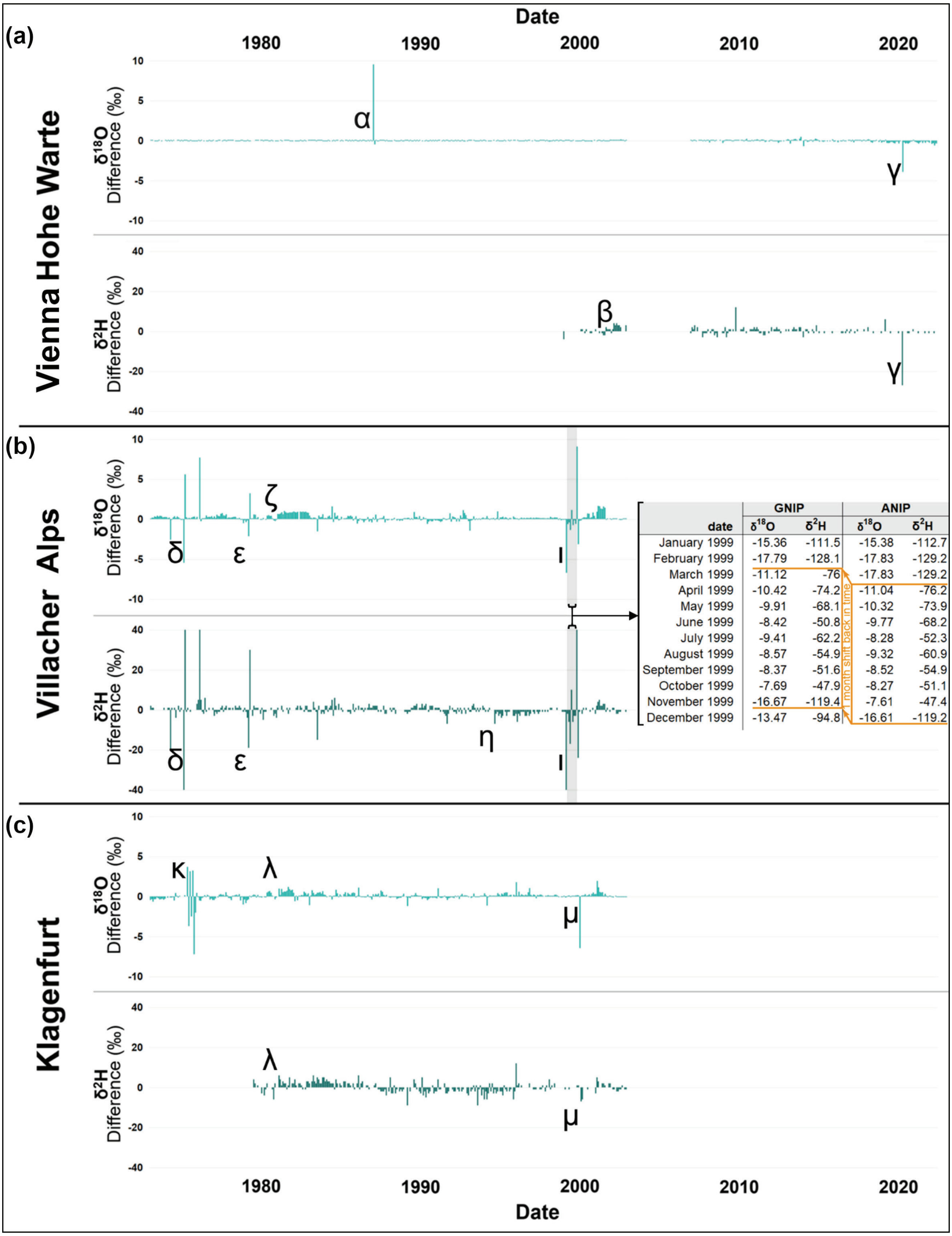

Figure 6: Column charts showing the differences between the ANIP and GNIP values from the stations providing data for both networks: Vienna **(a)** Hohe Warte, **(b)** Villacher Alps, and **(c)** Klagenfurt. Some of the point and interval anomalies discussed in Section 3.3. are annotated by Greek letters. *α*: January 1987, *β*: February to August 2002, *γ*: May 2020, *δ*: February to March 1975, *ε*: March to April 1979, *ζ*: January 1981 to January 1983, *η*: September 1994 to July 1997, *ι*: March to December 1999 with inset table showing the corresponding data, *κ*: May to December 1975, *λ*: February 1981 to May 1986, *μ*: January 2000

- February 1976: the ANIP values are clearly too high compared to its neighbors for both parameters,
- March to April 1979: the February and March values in the ANIP record are probably duplicates. Thus, the data could be corrected by replacing the March value with the April value, and leaving a gap in April would provide an acceptable agreement. This is confirmed by the GNIP values being similar to the neighboring stations' values.
- January 1981 to January 1983: the average difference between ANIP and GNIP $\delta^{18}O$ values is 0.8‰ with systematically more positive ANIP values,
- July 1983: the ANIP and GNIP values remarkably differ for both parameters, with ANIP values being more negative than the GNIP values.
- September 1994 to July 1997: the δ^2H values are more positive than the ANIP values, by ~2‰ on average.
- March to December 1999: this is the period with the largest deviations on record. The ANIP values in February and March are probably duplicates. The time series could be corrected by removing the March value and shifting the following nine-month period by one month backwards (see inset table in Fig. 6b). Leaving a gap in December would provide an acceptable agreement. This is confirmed by the GNIP values which are similar to the neighboring stations.
- February 2001 to August 2001: the ANIP values are more positive than the GNIP values for both parameters. The *d*-excess values range between -0.7 and 7.7‰, suggesting a secondary evaporation effect, which should be noted in the ANIP dataset.

At Klagenfurt, the ANIP dataset has consistently more negative values than the GNIP database over the first two years of overlapping $\delta^{18}O$ records, i.e., by -0.22‰ on average. Strong differences are observed in 1975, spanning from -7.22 to +3.7‰ (Fig. 6c). Comparing the data with neighboring stations revealed that the misfit stems from the GNIP values which should be shifted backwards in time by one month. From 1981 to 1986 there are systematic discrepancies between the GNIP and ANIP datasets, with a mean difference of +0.31‰ and 2.2‰ for $\delta^{18}O$ and δ^2H, respectively. Also, the ANIP values are much higher than the GNIP values in January 1996 for both parameters, while the $\delta^{18}O$ ANIP values are higher than the GNIP values in January 2000, and the δ^2H GNIP values are higher than the ANIP values from March to April 2000. In the case of January 2000, the ANIP values show an unprecedented *d*-excess = 46.7‰, suggesting that the $\delta^{18}O$ record of -15.13‰ can be erroneous in the ANIP record. The last period of systematic discrepancies between ANIP and GNIP datasets over multiple months occurred in 2001, with much higher ANIP values than the GNIP values (Fig. 6c).

4. Conclusions

Systematic screening of the precipitation stable isotope records can reveal potential errors in the database. Depending on how extensive these errors are, they can propagate significantly altering isotopic characteristics e.g., LMWL. When using the data for hydrogeological issues, this can lead to misinterpretations that can be prevented if the raw data used has been checked for consistency in advance and corrected if necessary. The documented steps of the screening procedure can serve as a uniform procedure for detecting and handling of such typical database errors which could be applied also for other precipitation stable isotope data archives. It can be concluded from the presented examples that blindly applying a static *d*-excess cutoff value or simply looking at the cross plot of $\delta^{18}O$ vs. δ^2H, will not provide sufficient information to detect errors in specific cases when (i) only $\delta^{18}O$ or δ^2H is available (e.g., Flattnitz) (Tab. S1), or when (ii) both parameters are mutually shifted in time (e.g., Bad Bleiberg) (Tab. S1).

The described inconsistencies may be impossible to avoid when operating a monitoring network over decades and through different states of database operation and maintenance. The study demonstrated a systematic distance-based outlier detection approach for identifying and resolving potential errors screening the database of the Austrian Network for Isotopes in Precipitation. Users of precipitation stable isotope databases should apply their own plausibility checks which are suitable for the analysis goal and critically scrutinize the raw data and consider the error flags.

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Supplementary material

Table S1 List of records with potential inconsistency and possible explanations / solutions, numerical documentation:

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